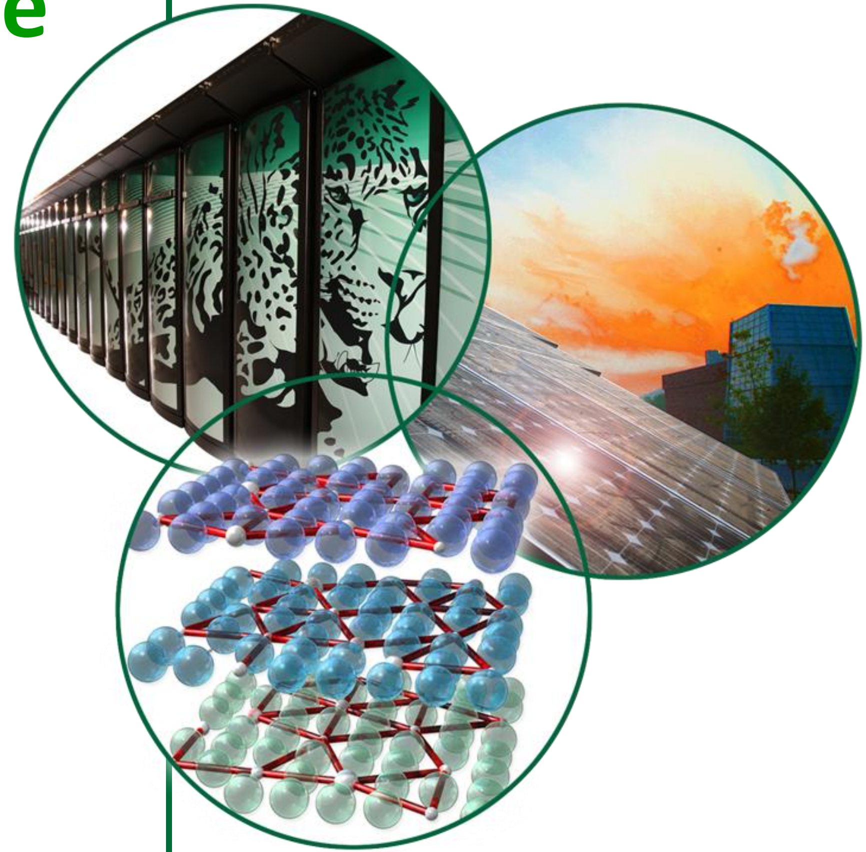
Data Generated and Needs for Carbon Dioxide Capture and Storage



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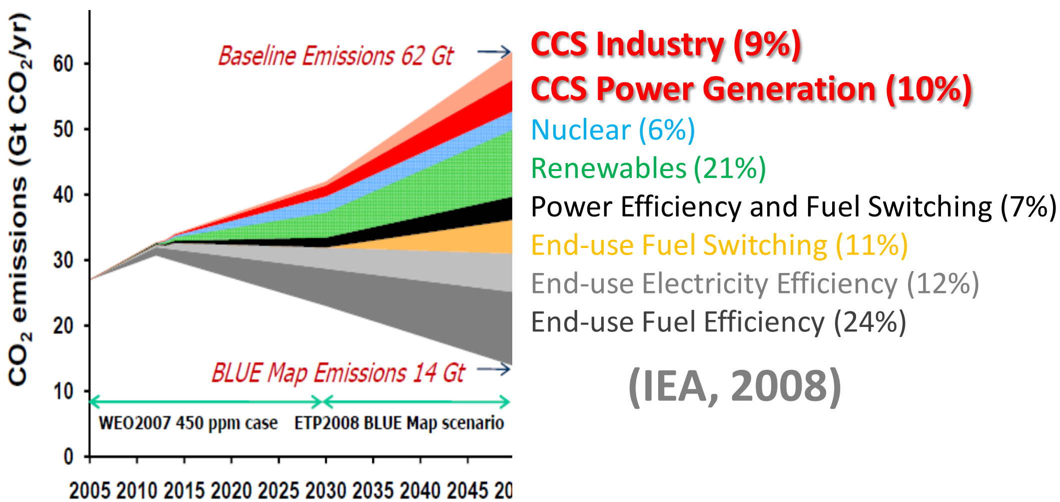
ESIP Summer Meeting| Energy Cluster| July 22, 2010

Scale Matters

Magnitude of the Problem:

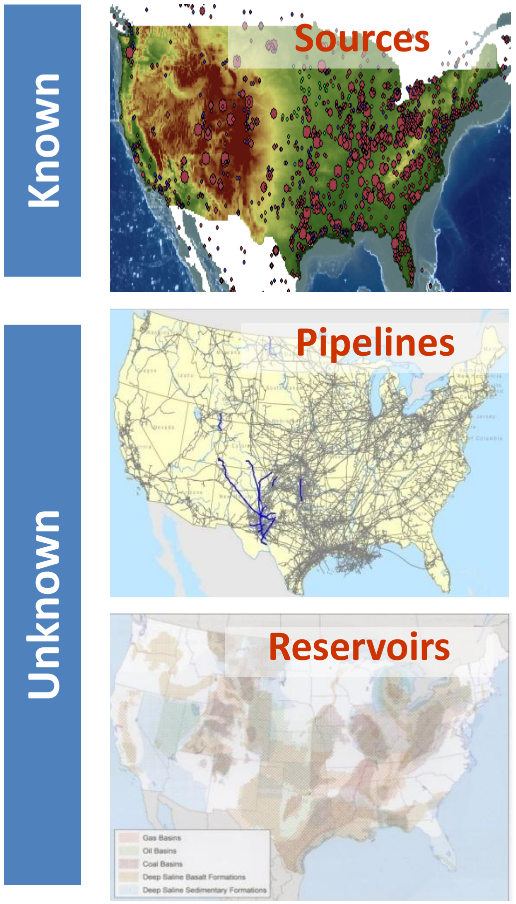


(IEA, 2008)

- **Generalize scaling issues that arise from the interactions and patterns they form.**
- **Deploy as efficiently as possible:** Understand Returns to Scale to locate, organize, and guide deployment of sustainable energy systems.

Carbon Dioxide Capture and Storage (CCS)

- **Capture CO_2**
  - Typically from large stationary sources
- **Transport captured CO_2**
  - Most efficiently by pipeline
- **Store CO_2**
  - By injection it into geologic reservoirs



CCS Data Generated and Needed

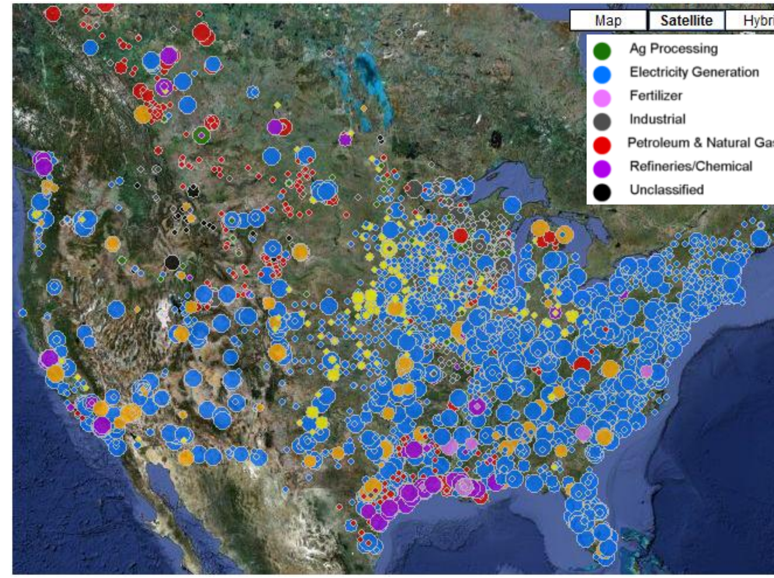
- **Modeling and Analysis**
  - Producing and analyzing policy-relevant case-study data
- **Experimental, Demonstration, and Project Data**
  - Incorporating and analyzing actual existing data
- **Integrating and Informing**
  - Combining into integrated decision-making frameworks

Large Stationary CO_2 Sources (in North America; NETL, 2008)

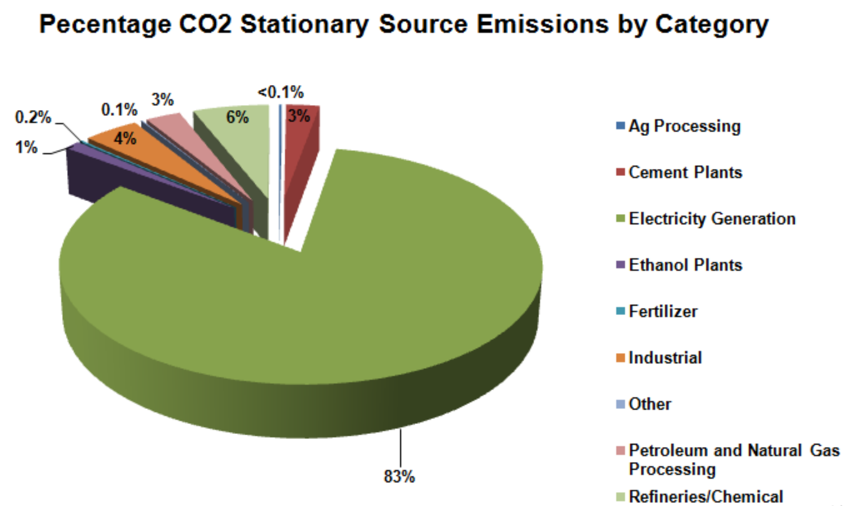
- **UNITED STATES:**
  - 4,800 Sources
  - 3,300 Mt CO_2 per year

Estimated Capture Cost by Facility ($/t$CO_2$)

Gas processing: $16-24
Chemicals: $26-30
Biomass(power):$41-43
Coal (power): $35-55
Pulp and Paper: $54-68
Gas (power): $56-74
Cement: $58-102
Iron and Steel: $61-71
Gas (synfuels + H_2): $61-101
Biomass (synfuels + H_2): $72-105

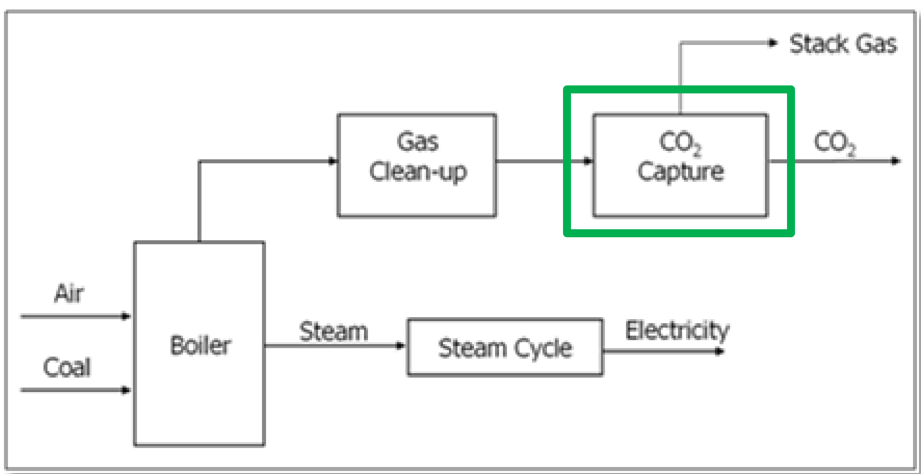


- **INDUSTRIAL ORGANIZATION:**
  - Coal-fired electricity generation dominates emissions sources
  - But low-cost capture sources are not coal



CO_2 Capture Technologies and Source Operations

- **Each source has its own characteristic operating characteristics and load**

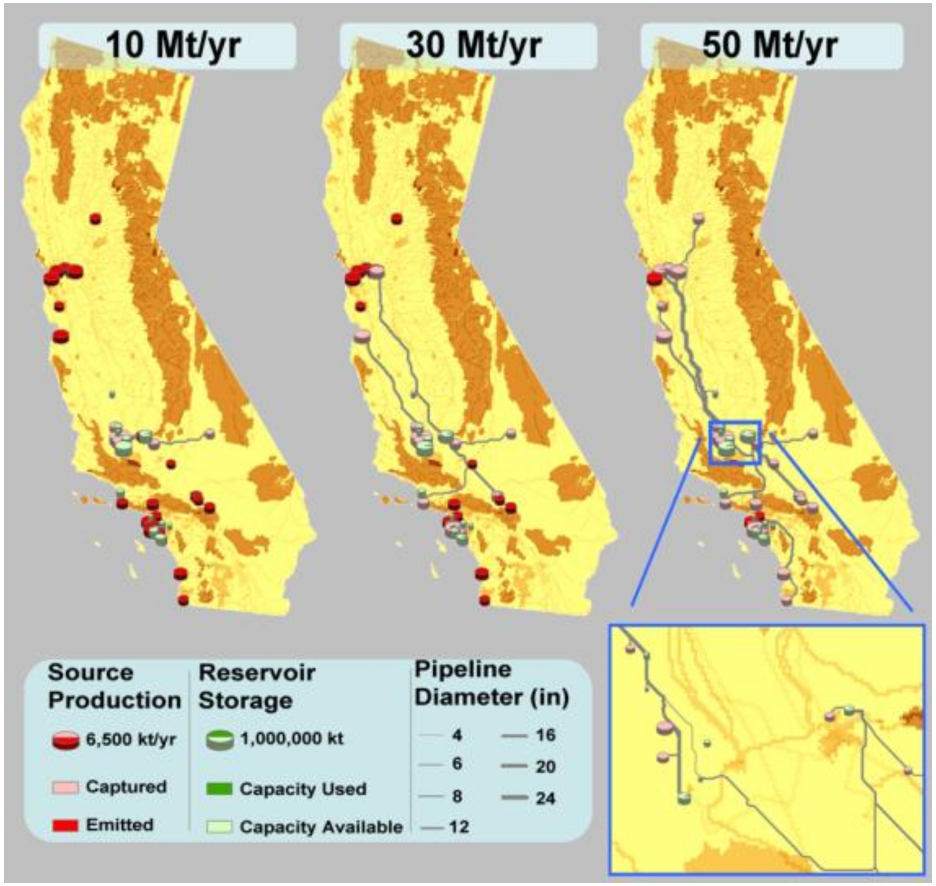


- **CO_2 capture options and processes depend on the specifics of the systems:**
  - Pre- and post-combustion capture:
    - Physical absorption (e.g., Selexol)
    - Chemical absorption (e.g., MEA)…
  - Oxy-fueled combustion:
    - Combust fuel in pure oxygen; separate oxygen from air prior to combustion.
- **Several technologies need to be developed.**
  - Cleans more than coal.
  - Cost and energy penalties are considerable.

Adapted from: IEA (2008), EIA (2009), and IPCC (2005).

Pipeline Transportation of CO_2

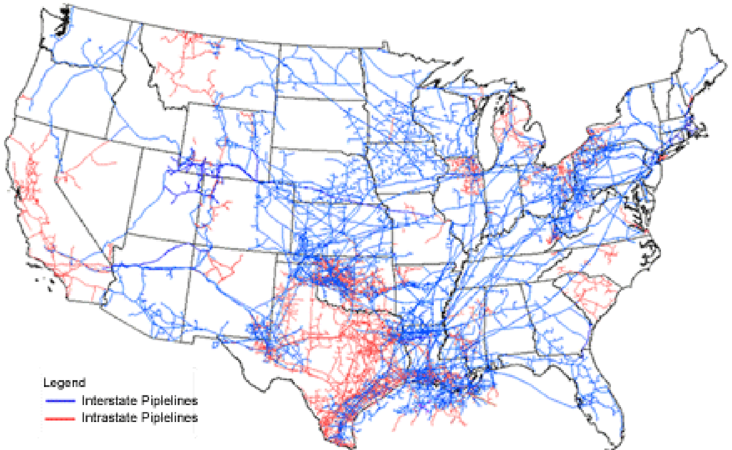
- **Siting issues – especially at large scales – can be significant.**



Middleton and Bielicki (2009a)

Construction of Green Pipeline, Denbury Resources Baton Rouge, LA. May, 2009

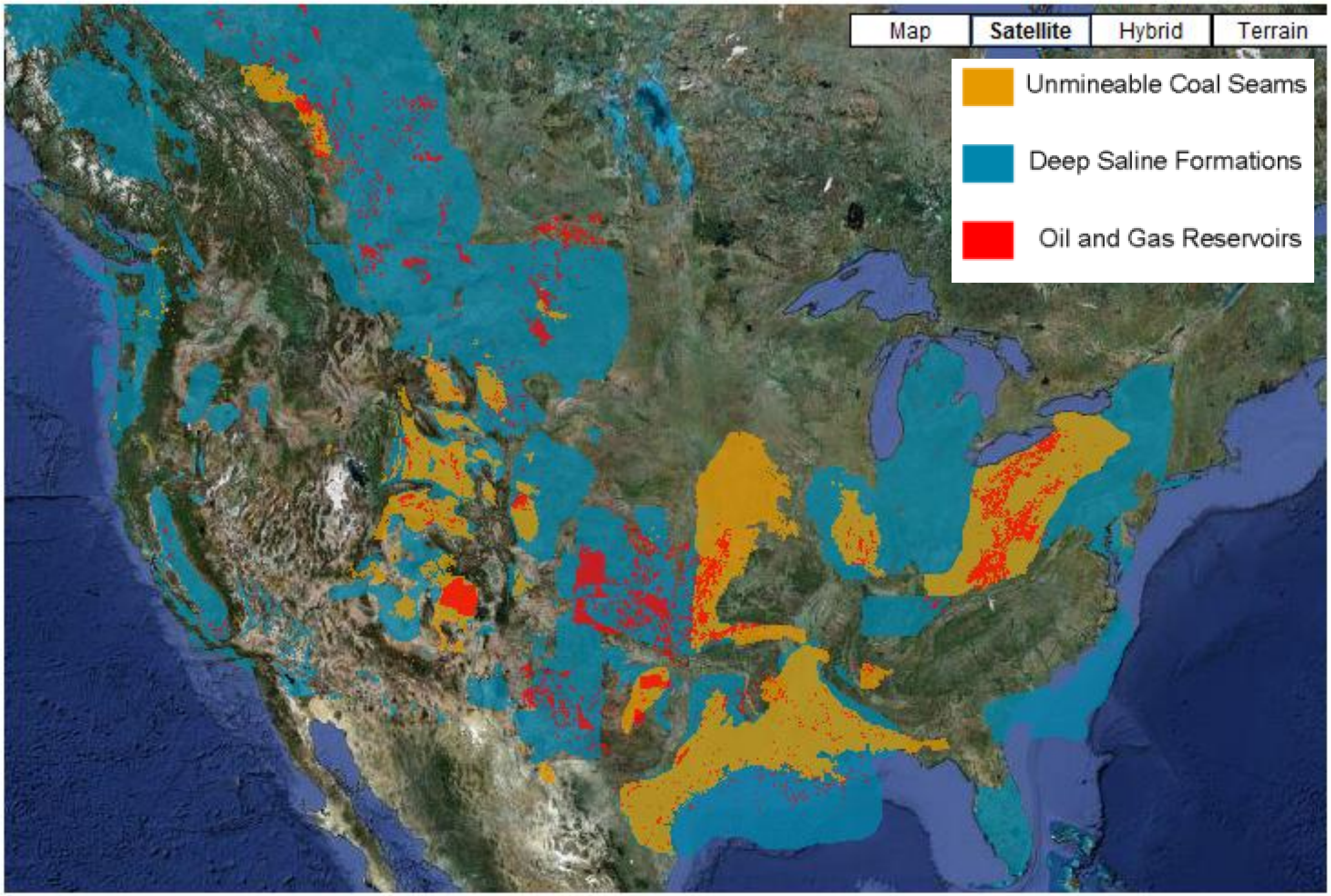
The national natural gas mainline transmission grid is made up of approximately 217,000 miles of interstate pipelines and 89,000 miles of intrastate pipeline.



Source: Energy Information Administration, Natural Gas Transportation Information System, Natural Gas Pipeline Maps Database (December 2008)

http://tonto.eia.doe.gov/energy_in_brief/images/charts/ngpipelines_map_small.png

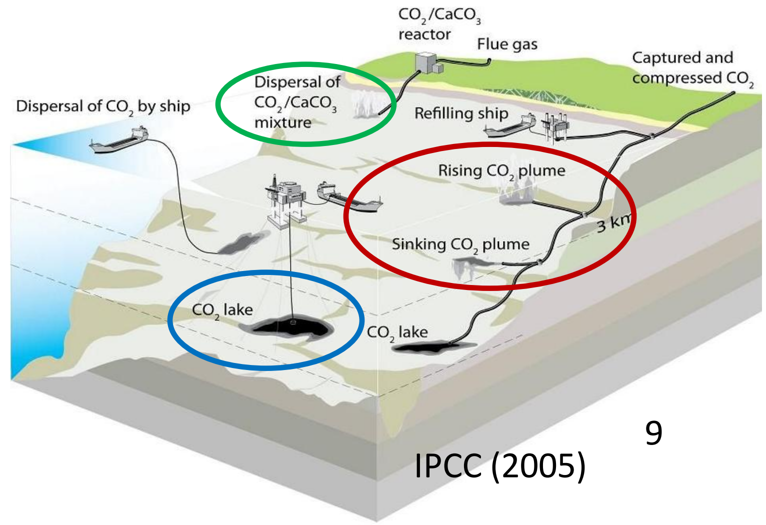
Conventional CO_2 Storage Options (NETL, 2008)



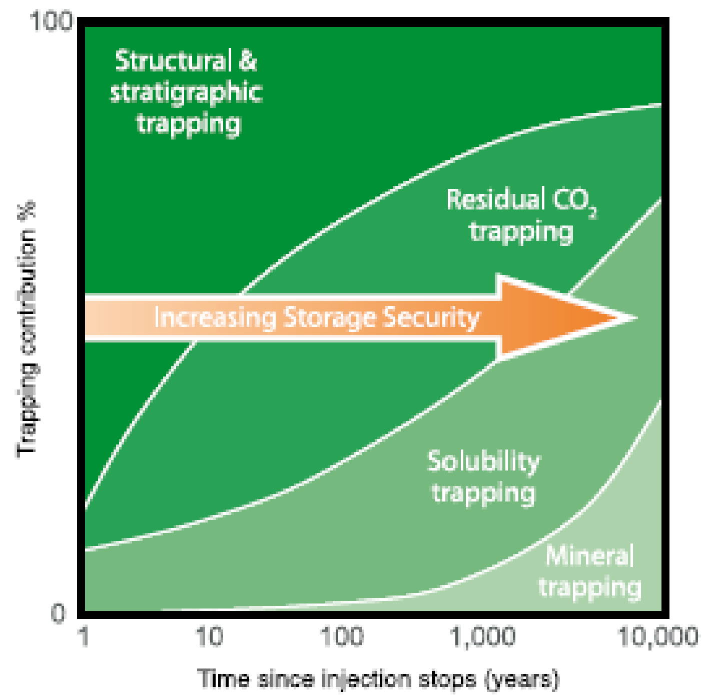
Other Storage Considerations

- **Ocean Disposal:** ~80% of atmospheric CO_2 ends up dissolved in the ocean… Bypass natural process by deliberate injection.

  Seawater | "Deep" seawater | Mineral carbonation



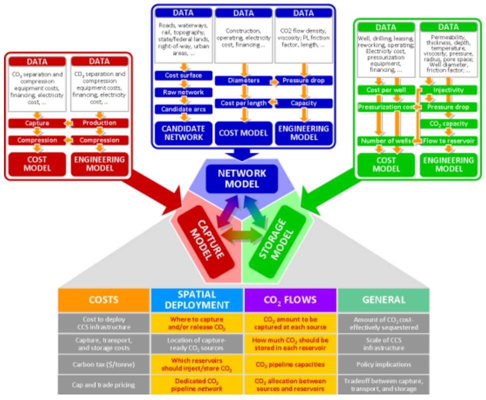
- **Storage Security:** Increases the longer CO_2 is underground.
  - **Carbonate Chemistry** (e.g., Lackner 2004) - React with mine tailings (e.g., serpentine), for example
  - **Deep sea sediment** (e.g., House et al, 2006) - Gravitational trapping, CO_2 hydrate formation(?)
  - **Basalt** (lava flows, rich in MgO and CaO) – Onshore, Offshore Basalt (e.g., Goldberg et al, 2008)



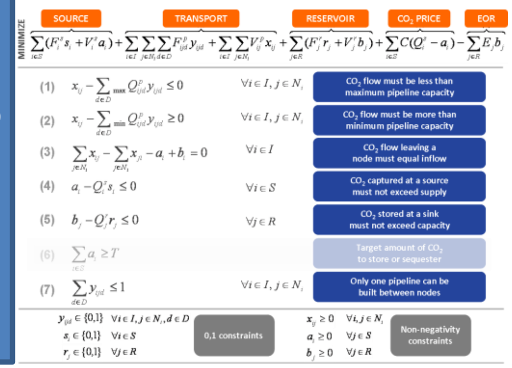
SimCCS Family of Models*

- **Models that spatially deploy integrated CCS systems based on**
  - Scale of CCS system (CO_2 target)
  - CO_2 price (from tax or cap-and-trade system)
- **Determines how and where CO_2 should be captured, transported, and stored.**
  - Combines engineering, geoscience, and economics
- **Realistically generates and routes transportation networks.**
  - Suggest "better" routes from overall system perspective.

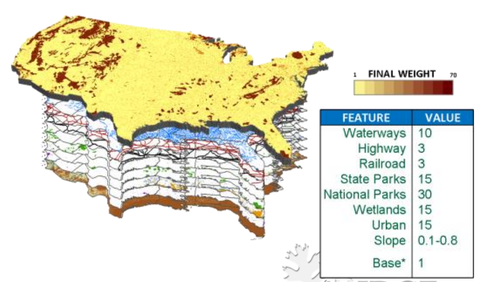
Engineering-Economic



Mixed-Integer LP



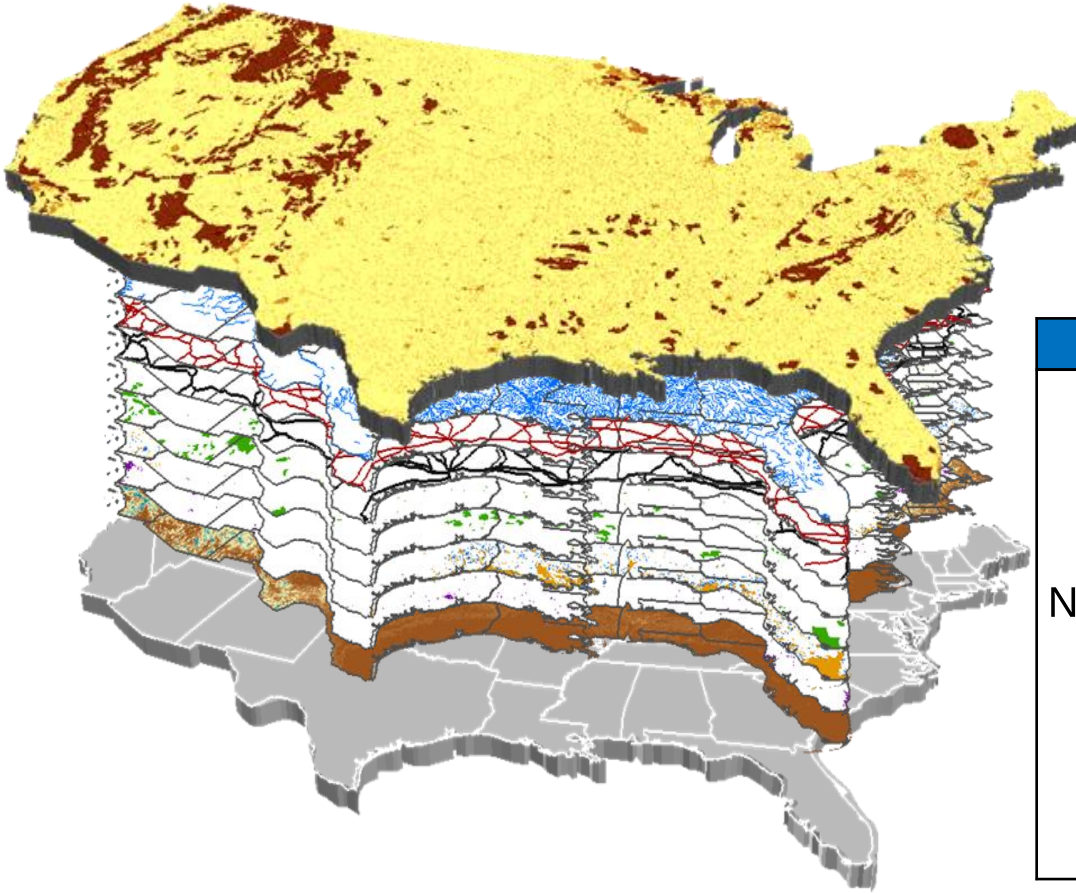
Cost Surface



*Bielicki (2009a); Middleton and Bielicki (2009a, 2009b); Kuby, Bielicki, and Middleton (2010); Middleton, Bielicki, and Kuby (2010);

Routing Pipelines

- **Shortest path algorithm incorporates social and physical topography:**
  - Relative cost of routing through cell (1km x 1km)



FEATURE	VALUE
Waterways	10
Highway	3
Railroad	3
State Parks	15
National Parks	30
Wetlands	15
Urban	15
Slope	0.1-0.8
Base*	1

California Infrastructure Example

37 Potential Sources (S37)

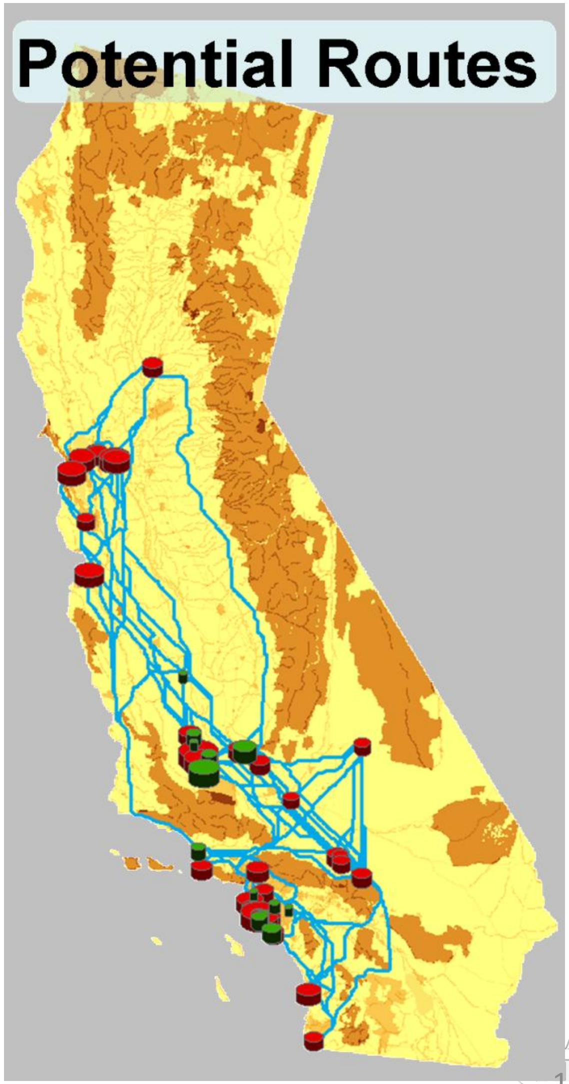
14 Potential Reservoirs (R14)

Potential Routes

- ***Between every S-R combination.***
- ***Avoid darker patches.***

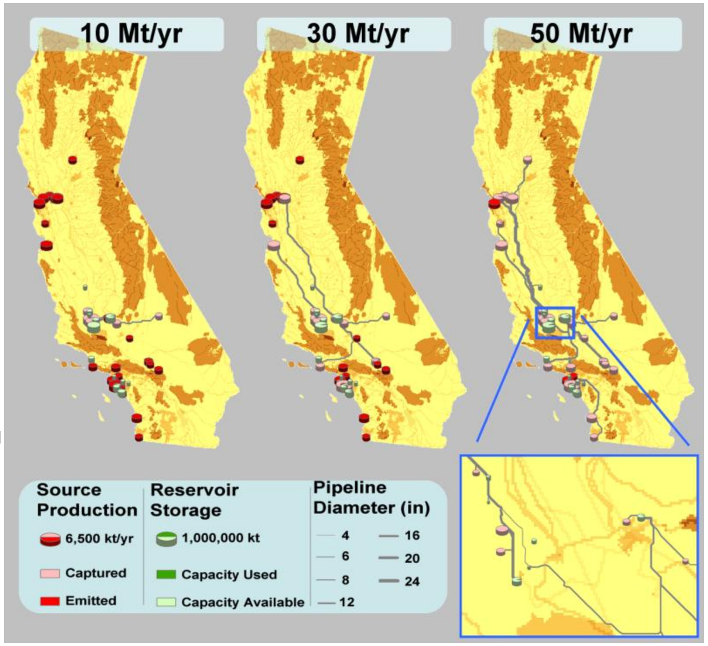
California		CO_2 Capacity [(S) kt/yr; (R) kt]		Estimated Cost [$/t_{CO2}$]	
Code	Description	Mean	S.D.	Mean	S.D.
S4	4 largest sources	3,889	1,108	39.86	0.18
S12	12 largest sources	2,886	962	45.09	7.80
S37	37 largest sources	1,752	986	44.17	7.12
SB23	23 largest (Bay area)	952	756	42.33	6.38
SLA18	18 largest (LA area)	1,358	765	45.35	7.50
R1	Largest CO_2 capacity oil field	410,554	-	3.68	-
R2	2 largest CO_2 capacity oil fields	328,769	115,661	2.75	1.32
R3	3 largest CO_2 capacity oil fields	270,643	129,710	2.78	0.97
R5	5 largest CO_2 capacity oil fields	210,718	123,115	3.86	1.80
R14	14 largest CO_2 capacity oil fields	110,639	105,917	4.01	1.15
R54-R5	6-54th largest	18,497	21,911	3.60	2.05

Estimated capacities and costs from Bielicki (2008) methodology applied to Westcarb data.

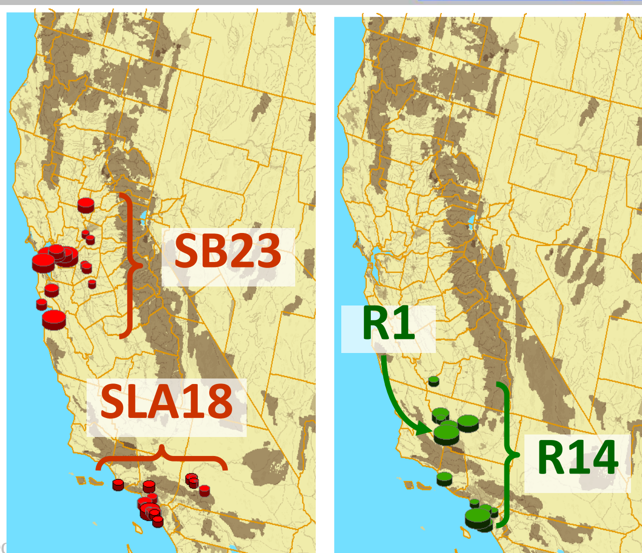


Example Case Studies in California

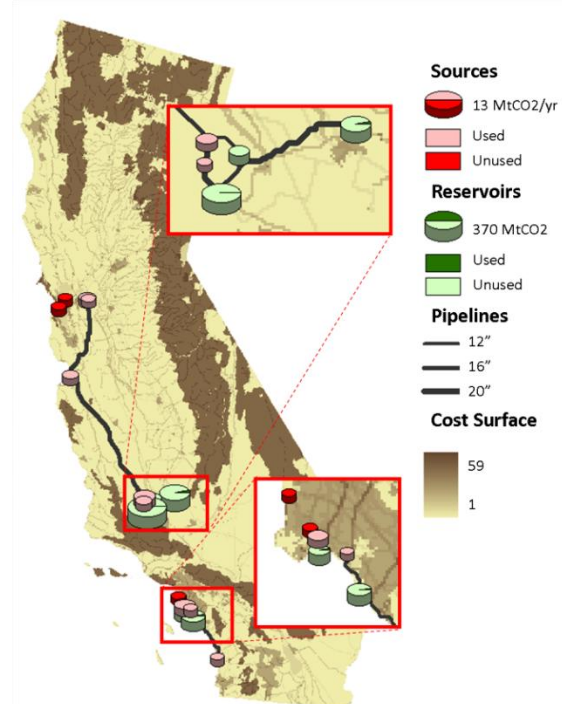
CO_2 Target: S37 R14

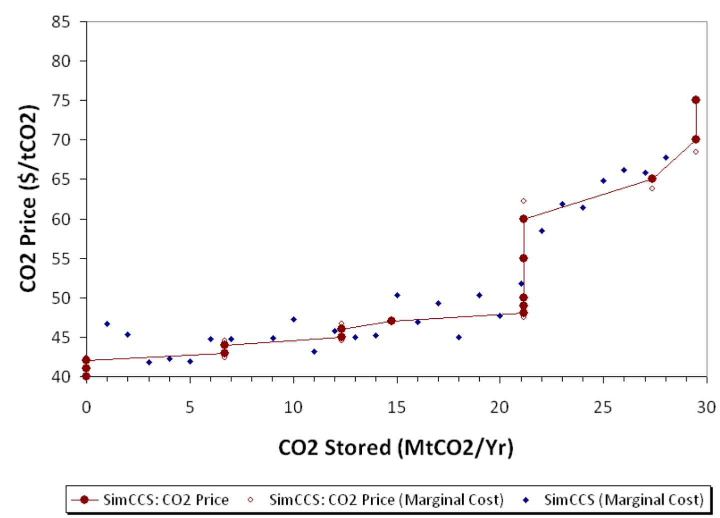


Spatial Clustering:



CO_2 Price: S12 R5





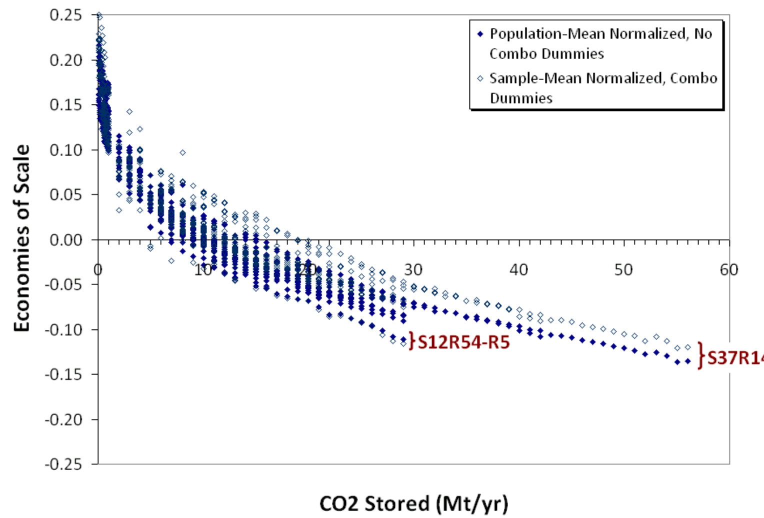
Generalizing Case Studies with Complicated Econometrics (Bielicki, 2008; Bielicki, 2009a)

$$
\begin{aligned}
ln(C) = \alpha_0 + \alpha^Y ln(Y) + \sum_i \beta_i^W ln(W_i) + \sum_i \phi_i^Z ln(Z_i) + \frac{1}{2}\delta^{YY}\left(ln(Y)\right)^2 + \cdots \\
+ \frac{1}{2}\sum_i\sum_j \gamma_{ij}^{WW} ln(W_i) ln(W_j) + \frac{1}{2}\sum_i\sum_j \psi_{ij}^{ZZ} ln(Z_i) ln(Z_i) + \cdots \\
+ ln(Y)\sum_i \rho_i^{YW} ln(W_i) + ln(Y)\sum_i \mu_i^{YZ} ln(Z_i) + \sum_i\sum_j \lambda_{ij}^{WZ} ln(W_i) ln(Z_j)
\end{aligned}
$$

***Y** = scale*
***W_i** = $cost_i$*
***Z_i** = vector of important things*

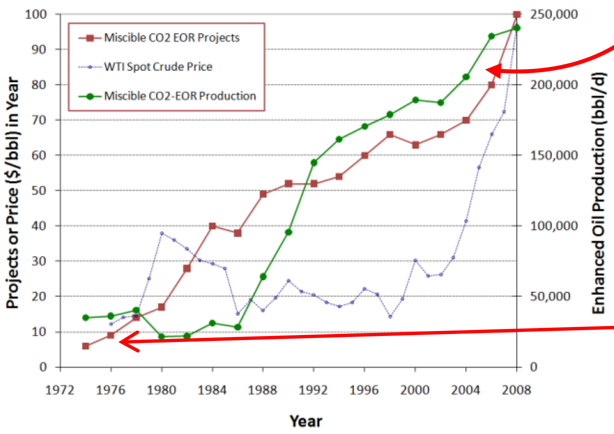
$$\varepsilon_{W_i} \equiv \frac{\partial \ln(C)}{\partial \ln(W_i)}$$

$$RTS \equiv \frac{1}{\sum_{i \in X} \varepsilon_i}$$



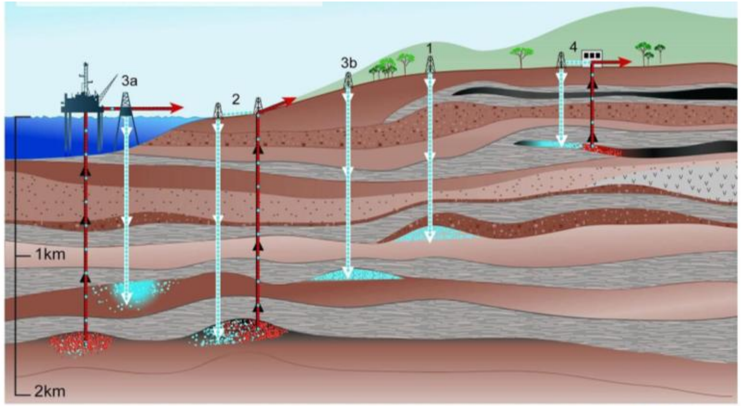
Actual Data: CO_2 Injection Experience

- **Enhanced Oil Recovery (EOR)** - Inject CO_2 into oil fields to enhance oil production.



Steady increase in the number of projects reported.

Have been injecting CO_2 for EOR since the early 1970's.

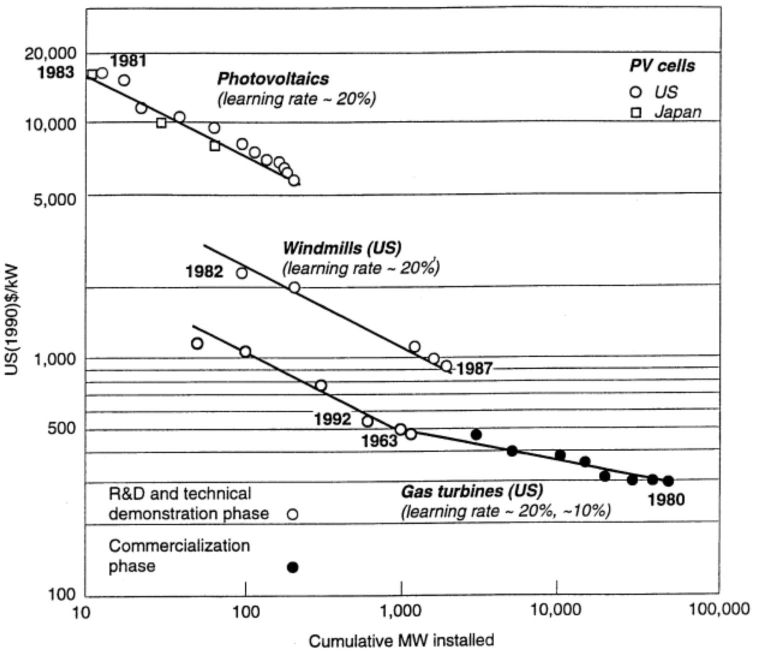


Technological Learning (Bielicki, 2009a; Bielicki, 2010)

- **Typical Learning Curve**

$$C_t = C_0 \left(\frac{Q_t}{q_0} \right)^{-\beta}$$

$C_{t,0}$ = Cost at (t, $t=0$)
Q_t, q_0 = Cumulative quantity at (t, $t=0$)
β = learning coefficient



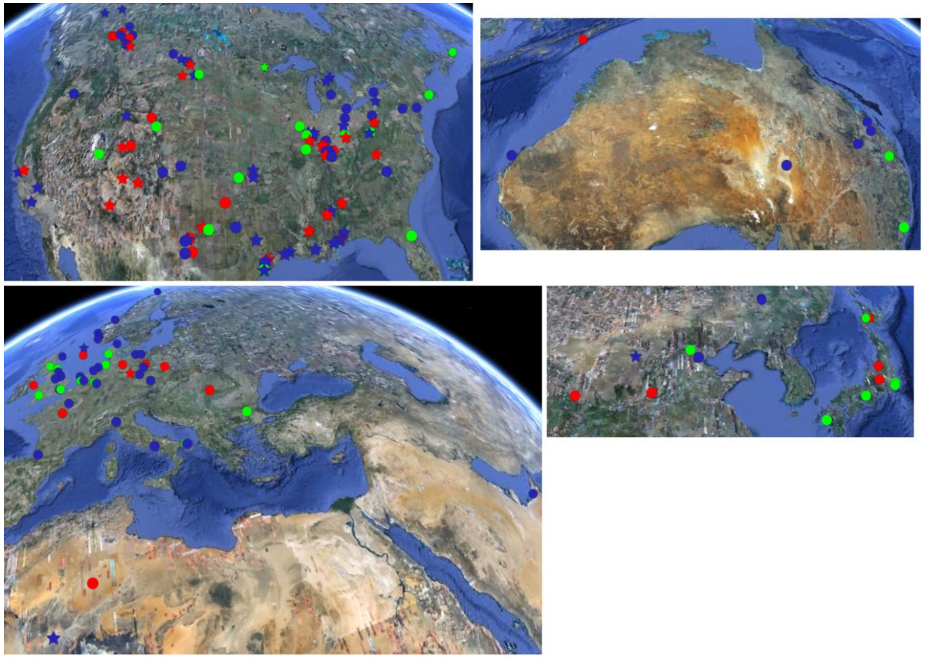
- **Learning for CO_2-EOR**

$$E_{bbl/d,t} = e^{\omega \cdot a} \cdot q_{t-1}^{\phi} \cdot E_{bbl/d,t-1}^{\theta} \cdot Q_t^{\beta}$$

- **For CO_2-EOR**
  - Physical model of reservoir response
  - Control for depleting resource
  - Control for geology
  - Separate for project and operator spillovers

Integrated Data Needed

- Five industrial scale fully integrated CCS projects
- 129 documented CO_2 injection projects (GCCSI, 2009).



- **At present, data is mostly siloed, as is the knowledge and learning generated from it.**

Advancing CCS

- **A lot of data are being generated**
  - Highly specific, component and process
  - Very compartmentalized
- **A lot of data can be generated**
  - Case studies, simulations
- **Integration and common databases are needed**
  - For analysis across projects and activities
- **Integrative decision-making models are required**

Contact Information

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